Intelligent Approaches for Whole-Body Vibrations Attenuation problem of Seated Operators

Synopsis

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1.0 Introduction

Vibrations are inherent attributes of all mobile equipment because of their rotating and reciprocating parts. Vibrations are also caused by the equipment externalities such as excitations caused by the undulating profile of its travel path [1]. Vibrations generated intrinsically can be managed to some extent but the ones caused by externalities are random and sometimes of large amplitude. Such vibrations also get amplified when a rough profile is traversed. Vibrations are detrimental to system reliability but are inevitable due to system design and external conditions.

Human response to vibrations is a multidisciplinary topic, which finds convergence of diverse fields such as engineering, biomechanics, psychology and medicine. Operators and passengers of mobile equipment are exposed to health issues due to vibrations and this is an area of paramount significance. The impact of vibrations on humans is assessed in two broad categories: Whole Body Vibrations (WBV) and Hand-Arm Vibrations (HAV). Vibrations transmitted to the whole body of the operators of equipment through the interface of equipment and operator are termed as Whole-body vibrations. This interface is primarily the seat, in addition to seat support, steering wheel/handle and footboard of the seated operator. WBV are the subject of interest in material handling equipment, agricultural equipment, transport equipment, mining equipment, etc. Hand Arm Vibrations also referred to as Hand transmitted vibrations, are the oscillations transmitted to the hands and arms of operators of equipment while the equipment is in use. Examples of HAV causing equipment are chain saws, jack hammers, hand drilling machines, etc.

Depending on the complexity of the model involved in the investigation, various degrees of freedom have been analyzed by researchers. These involve vibration measurement along three translational axes, viz., x, y, z axes and corresponding three rotational axes. The degrees of freedom get enhanced with additional contact points with road/floor as well as number of constituent components of system which influence suspension.

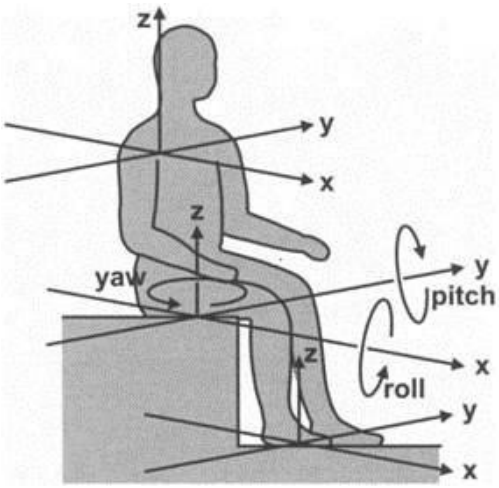

Fig. 1: Whole-body vibration axes for a seated operator/driver at feet, seat and back [Adapted from British Standards Institution (1987). Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. BS 6841. London: British Standards Institution.]

Most studies have shown that vertical axis has the highest impact on health and is the primary axis of focus in vibration measurement. With the advancements in instrumentation, it has been possible to measure the vibrations along multiple axes economically, in real time, using tri-axial accelerometers.

This work is focused on impact of WBV on human body. Studies have shown that chronic exposure to WBV in the frequency range of 0.5 Hz to 80 Hz are detrimental to human health. Thus, WBV is generally studied in this frequency range. In some European Union countries, spinal injury caused by WBV is considered as an occupational hazard and is compensable (for example, in Germany, vibration induced spinal disorders are compensable).

Various metrics have been used to measure WBV which include acceleration, energy absorption, peak displacement, duration of vibration exposure. Professional operators of seated mobile equipment are exposed to Whole body vibrations over long periods in their lifespan[2]–[4]. This has serious consequences on their health and quality of life. Plethora of literature is available citing the adverse effects of WBV[5]–[7][8][9], [10]. But due to non-availability of viable technologies, this problem could not be resolved satisfactorily in the past. Health degeneration of the vulnerable operators continues unabated on the other hand. This provides the motivation and urgency to take up research on WBV attenuation on priority basis.

Intelligent systems have been successful in solving many real-world problems. Few other technological developments such as, magneto rheological dampeners, have enabled deployment of intelligent systems

in suspensions. This combination is an area of active research for attenuation of WBV. However, such systems are in their infancy and their deployment on material handling equipment is quite limited. This current research aims to explore intelligent systems strategies as a solution to the WBV problem, paving the way for safer material handling operations.

2.0 Whole-body Vibrations and health issues

One of the major health issues arising out of chronic WBV exposure is lower back pain. This is caused by the vertebral disc degeneration or sometimes called herniated disc. Other human body systems such as vestibular system, gastro intestinal organs, shoulders and neck are also impacted by WBV[11][12][13][14][15]–[17].

2.1 Pathogenesis of WBV induced degeneration of vertebral column

Chronic exposure to vibrations of high intensity causes mechanical overload on the human vertebral column. This damages the spine because such vibrations do not occur under normal conditions to which humans have adapted for thousands of years[18].

Another hypothesis suggests that vibrations reduce the diffusion process in the intervertebral discs. Small nutrients such as oxygen and glucose are almost entirely supplied to the disc cells by diffusion. Removal of the metabolic wastes such as lactic acid from the cells also happens by diffusion. Concentration of lactic acid is responsible for nerve irritation and pain. Impaired nutrition leads to cell death, eventually causing starvation and flattening of disc. This disc degeneration causes lower back pain[19].

Biodynamic experiments with vertical vibrations in seated condition show that resonance of lower trunk and vertebral column occurs in the frequency range of 3 to 5 Hz.

2.2 Meta-analysis and Systematic review linking WBV exposure to lower back pain

Bovenzi and Hulshof, conducted a meta-analysis of epidemiologic studies using articles published in the period from 1986 to 1997. These articles were generated from several databases linking occupations having exposure to whole-body vibration in various equipment to the lower back pain. Their systematic search generated 45 articles using several databases. These articles were then subjected to evaluation criteria to assess the sufficiency of provided information to link lower back pain and WBV exposure. Based on this screening, a total of 28 articles were excluded from further evaluation. Most of these

exclusions were due to lack of sufficient qualitative information on WBV exposure. 4 articles had serious methodological shortcomings such as lack of external control group. Some articles had incomplete description of other potential confounders or inadequate control for such confounders. Finally, 17 articles were found to satisfy the selection criteria as per their scoring system. These articles covered 22 occupational groups comprising of bus drivers, forklift operators, truck operators, operators of earthmoving equipment and commercial travelers. The final analysis involved cross sectional studies for 13 occupational groups, cohort studies for 4 groups, case control type for 1 group and both cross sectional as well as follow up data type study for remaining 4 groups. This systematic review and meta-analysis found clear evidence of increased risk of occurrence of LBP disorders due to WBV exposure [20].

In another systematic review by Burstrom et al.,[21] articles published till 31st December, 2013, were evaluated linking WBV to LBP and sciatica. Their search followed the guidelines of preferred reporting items for systematic review and meta-analysis (PRISMA). PRISMA guidelines consists of a checklist of 27 items for reporting systematic review or meta-analyses. It was proposed as an evolution of earlier Quality of Reporting of Meta-analyses (QUOROM) for reporting systematic review or meta-analysis based on conceptual and practical advances [22]. A total of 57 original articles were considered in this systematic review. Majority of these demonstrated an association between WBV and lower back pain and sciatica. The magnitude of this association was also estimated in this meta-analysis. After examining the title, abstract and scrutinizing the full text, 27 articles met the inclusion criterion having WBV exposure assessment and outcome in the form of LBP and/or sciatica. This analysis showed that the pooled odds ratio had a doubled risk for both LBP and sciatica due to WBV. This is a scientific evidence that WBV exposure increases the risk of LBP and sciatica. The novel finding of this review is also in demonstrating that literature has evidence of the risk of sciatica due to exposure to WBV[21].

However, other confounding factors such as static position for long duration and twisting of trunk during the operations could also induce musculoskeletal disorders such as lower back pain. But the impact of each of these factors studied in isolation, on the inception and development of lower back pain was limited in literature.

2.3 WBV as a risk factor for reduced alertness

Laboratory studies had shown that WBV exposure leads to fatigue which can result in reduced alertness. Fatigue is one of the main causes of road accidents. Fatigue as defined by Thiffault, is the process of shift of the driver's state of wakefulness towards the sleep end of the sleep-wake continuum. As per police reports in Canada, fatigued driving and falling asleep are the main contributing factors for over 60 fatal collisions per month involving heavy motor vehicles [23]. The count of fatigue-related accidents is also probably understated because it is difficult to isolate the accidents attributable to fatigue triggered by drowsiness from other factors [24]. So, we can expect the fatigue related drowsiness to be the cause of many more accidents than recorded.

In another study, seated volunteers were exposed in the laboratory set-up to Gaussian random vibrations of 1-15 Hz frequency bandwidth at 0.2 rms – 2 rms for 20 mins. They were then subjected to psychomotor vigilance test (PVT) after WBV exposure. The results suggest that WBV exposure of even 20 minutes can cause significant drowsiness impairing psychomotor performance [25]. Reduced vigilance is a serious safety hazard when operators of critical equipment such as Forklifts, Overhead cranes etc. are affected.

The impact of WBV dosage on vigilance level was analyzed in another interesting study. In this study, truck drivers were exposed to two different WBVs over the course of a workday and workweek. One truck had the industry standard conventional seat while the other had active vibration canceling seat. This had resulted in significant reduction in WBV exposure in the latter set. Driver vigilance was measured immediately before and after each shift using a 10-minute sustained attention reaction time task which is referred as psychomotor vigilance task (PVT). In the PVT, the subjects are presented a visual stimulus to which they respond by pressing a button. Research shows that fatigue and sleep deprivation results in increased reaction time to respond to stimulus. Reaction time is the milliseconds taken to respond to the stimulus. PVT has been widely used to measure vigilance and is considered as a good indicator to measure driver drowsiness [26]. This study showed that a reduction in WBV exposure was associated with a reduction in response times in PVT. This implies that the vigilance level had reduced due to increase in WBV. This study indicates that reducing WBV can aid in sustaining vigilance level which in turn reduces the risk of road collisions [27].

In an industrial setting, WBV reduction can aid in sustained alertness of operators on job. Fatigue caused by WBV can be regarded as a threat to safety at workplace.

2.4 Impact of WBV on other systems of human body

WBV is known to affect various other systems of human body as well. In a study involving 97 crane operators who are exposed to WBV and the control group of 48 pulpit operators, greater incidence of shoulder pain and lifetime prevalence of neck pain attributable to WBV was observed. It was also found that crane operators exposed to vertical accelerations greater than 0.4m/s^2 had more time loss from work due to back pain when compared to others exposed to less vibrations [28]. In another study, WBV was found to be the risk factor impacting the neck and shoulder, gastro-intestinal system, female reproductive organs, vestibular system and peripheral veins [29]. However, when compared to the plethora of evidence available linking WBV to lower back pain, there is a weak epidemiological support for WBV-induced disorders affecting other human systems.

2.5 Other Confounding factors present concurrently with WBV and linked to health issues

Operators of mobile material handling equipment are often exposed to concurrent factors along with WBV in work environments. Some of these concurrent factors may also be partly responsible for the health issues attributed to WBV. These confounding factors can be physical, chemical or behavioral. Physical factors such as static position for long duration, awkward postures such as twisting, bending, heavy lifting, temperature extremes, etc. cannot be ruled out in many applications. In one of the studies, the combined exposure of WBV and awkward posture was investigated among 102 professional drivers measured at different work locations. It was found that the daily vibration exposure with odds ratio of 1.69 and the index for awkward posture with odds ratio of 1.63 are significantly correlated to LBP. This novel approach combining the quantitative measures for WBV and awkward posture show its correlation with occurrence of LBP [30]. These can be considered as the factors which are under the control of the employers and their management.

Work environments of mobile equipment often have higher concentration of exhaust fumes and chemicals which contribute to the health risks. Behavioral factors such as smoking, diet, lack of exercise, on-job factors such as rotating shift-work, stress and genetic predisposition can also have their impact on the health of operators. However, the cross-sectional studies in which the control group was exposed

to all other factors except WBV, have recorded a lower risk for the health issues when compared with the study group exposed to WBV. Cohort studies, systematic reviews and meta-analyses of available literature have also established WBV as a causal factor for the health issues.

To evaluate the intervention strategies for mitigating these risks, it is necessary to measure the present level of exposure and estimate the threshold value beyond which the damage is pertinent.

3.0 WBV Measurement methodology and Standards adopted internationally

Scientific community is more or less unanimous in recognizing WBV as the causal factor for the observed health issues. So WBV exposure reduction is of paramount importance. In spite of the large number of studies, the threshold WBV dosage beyond which the health effects are cognizable and its measurement methodology continues to evolve. This anomaly is partly due to the difference in genetic predisposition or the other confounding factors at play resulting in dissimilar response level of operators when exposed to similar WBV dosage.

The primary data for WBV analysis involves measurement of acceleration of human body or the acceleration of vibration source surface. This acceleration is measured in three orthogonal axes – x, y, and z using triaxial accelerometers. However, the dominant axis subjected to continued vibrations is generally the z-axis which is the vertical direction from floor passing through the seat and/or feet of operators/drivers towards the head. WBV dosage values are then derived from this primary data depending on the adopted guidelines.

The applicable guidelines for WBV exposure are also slightly different depending on the standards adopted in the respective geographical region [31]. International Organization for Standardization (ISO) has 165 members as on 2020 and its standards are widely accepted. ISO standards are adopted by consensus by member countries. ISO standards relevant for WBV analysis are covered in section 3.1.

These standards provide a scientific basis for the measurement of WBV and controlling the associated hazards. The standards also aid in formulating a uniform criterion for evaluation and a basis for other contractual agreements. As the standards are reviewed periodically for their validity and updated based on the latest body of knowledge, they provide a suitable benchmark for directing the efforts in developing WBV attenuation strategies. The standards are advisory in nature and exposure limits provided are not legally binding on all the member countries. However, these provide the basis for

legislation by respective member countries, after which they can become legally binding. For example, Germany has passed a legislation (German Ordinance on noise and vibration of 6th March, 2007) transposing the EU directives on vibration: 2002/44/EC into German Law. The Technical Rules on Vibration (TRV) of March 2015 provide information on its implementation.

3.1 Applicable ISO Standards for WBV measurement:

- ISO 2631-1(1997): This establishes the WBV boundaries for continuous steady state vibrations.
- ISO 2631-5(2018): This standard establishes the guidelines for WBV due to transient shocks.
- ISO 10326-1: This standard provides the guidelines for comparison of operator seats for input vibration and operator mass.
- ISO 16063-21: This standard provides the guidelines for calibration of accelerometers.
- ISO 8608(2016): This standard specifies a uniform method of reporting measured vertical road profile data for the classification of roads in based on road roughness (into eight classes, viz., A to H).

3.2 Alternate Standards for WBV

- EU Directive 2002/44/EC: This obligates the employers and others to investigate and protect the workers exposed to WBV. In this the 'action limits' and 'exposure limits' are specified as legal norms.
- BS 6841:1987: British Standards are the first national standard and remains one of the active ones. However, the independent development of these standards is becoming rare, with most of their activities being adoption of CEN or ISO standards.

3.3 Modelling of the system:

The first challenge in WBV attenuation is that its model should be realistic. In WBV analysis, the lumped mass and anthropometric models are most commonly used. However, other models such as finite element model have also been used in literature. Lumped mass model involving mass, springs and dampeners is preferred for its simplicity and fairly realistic analysis of vibrations. In this, the subject operator is modelled as a point mass [32]. The major limitation of this model is that it does not consider the individual contribution of the stiffness and dampness of the biological tissues. However, it has been

found to be satisfactory for mathematical simulation and comparison of various seat models. Anthropometric models are the physical models. They usually are not representative of the human operators in entirety but they have a seat interface like a human operator and carry a lumped mass.

3.3.1 WBV measurements:

The most commonly used statistical measurements for WBV are root mean squared (rms) acceleration, peak acceleration and vibration dose value (VDV), normalized for 8 hrs. exposure. For random vibrations which are transient, rms remains fairly stable for the measuring period.

Mathematically, rms can be expressed as:

$$A_{w\,rms} = \sqrt{1/T \int_0^T aw(t)^2 dt}$$

Where $A_{w\,rms}$ is the frequency weighted rms acceleration, T is the measurement duration and aw (t) is the frequency-weighted acceleration at time t.

But when shocks are encountered, rms starts becoming insensitive. This is because the rms increase tends to be marginal after each shock with the passing of time. So, another measure which is a better representation of shocks due to vibrations is vibration dose value (VDV) which continually increases after encountering each new shock. It was developed based on the experimental observations which showed a 4th power relationship between vibration magnitude and discomfort.

Mathematically, VDV is expressed as:

$$VDV = \sqrt[4]{\int_0^T (aw(t)^4 dt}$$

Where T is the measurement duration, aw (t) is the frequency-weighted acceleration at time t.

In many analyses, individual measurements along orthogonal axes are combined. For rms measurements, vector sum of individual rms is carried. Thus,

$$A_{xyz} = \sqrt{a_{wx}^2 + a_{wy}^2 + a_{\omega z}^2}$$

And

$$VDV_{xyz} = \sqrt[4]{(VDVx^4 + VDVy^4 + VDVz^4)}$$

Further experimental findings indicate that the impact of vibrations in horizontal axes is much higher than vertical axes. So, many analyses have a scaling factor – kx, ky and kz for individual axes, where kx and ky are usually 1.4 while kz is 1.

Professional operators and drivers typically are exposed to vibrations during the entire work-shift. For uniformity in comparison of exposure dosage, the total daily vibration exposure rms value is normalized to an equivalent 8 hrs. continuous exposure. This is represented as A (8). But practically it is difficult and expensive to measure the vibration exposure for 8 hrs. Duration. So, it is usually measured for a shorter duration of test time, tn and normalized for entire shift duration.

Mathematically, A (8) is expressed as:

$$A(8) = \sqrt{(1/8(\ \sum_{n=1}^{n=N} awn^2 . tn}$$

Similar, mathematical extrapolation of VDV values is also carried out for normalizing to 8 hrs. exposure.

Daily equivalent static spinal compression dose (S_{ed}) is a measure of the static stress experienced by the spinal cord of human body.

Mathematically, S_{ed} is expressed as,

$$S_{ed} = [\ \sum_{k=x,y,z} (mk * Dkd\ )^6]^{\frac{1}{6}}$$

Where

Dkd = average daily dose value in corresponding axes,

mx = 0.015 MPa / (m/s^2),

my = 0.035 MPa / (m/s^2), and

mz = 0.032 MPa / (m/s^2)

Power spectral density (PSD) using fast Fourier transform (FFT) has also found application for modeling of road profiles during analysis of WBV.

3.3.2 General framework for Mathematical model formulation

Various approaches are used in literature for model formulation. One of the basic and commonly used models, is built with 2-Degrees of Freedom (2-DOF) involving a quarter (qtr.) vehicle and lumped masses as depicted in Fig. 2. It has been reported in literature that prolonged vibration exposure in

vertical direction is most damaging to human body. So, strategies based on this model are fairly effective in mitigating the health risks. For such a system, a quarter body of the vehicle is a fairly good representation of the vibration dynamics, as all rotational and horizontal translational movements are ignored. A typical multi-objective problem formulation is elucidated in this section.

The quarter vehicle model comprises of

- a random road profile which induces vibrations as input,
- the tire which is referred as unsprung mass and is generally modelled as a spring or spring and damper
- rest of the vehicle which is referred as sprung mass and has an external spring and damper

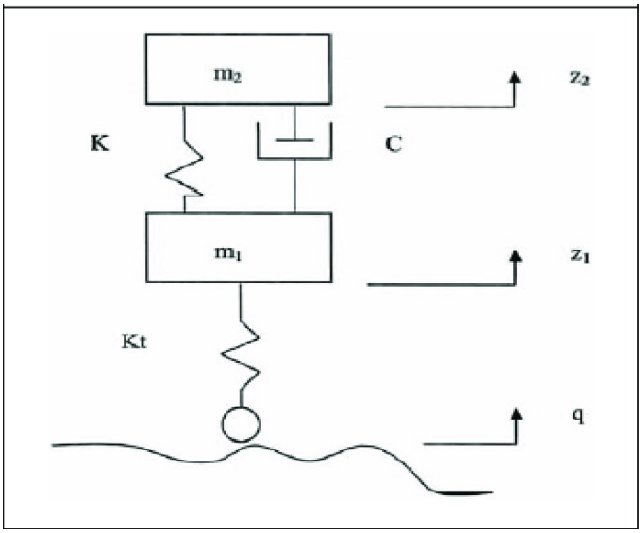

Fig. 2: Quarter vehicle model with 2-DOF on a random road profile

Few assumptions are made such as,

- Impact of rotational and other translational movements are ignored
- Spring stiffness and dampness have linear characteristics
- Frictional drag is ignored
- Tire is assumed to behave like spring

Applying Newton's equations, the 2-DOF system can be represented mathematically as below:

$$m_2 * \ddot{z_2} = K\,(z_2 - z_1) + C\,(\dot{z_2} - \dot{z_1})$$

$$m_1 * \ddot{z_2} = k_t\,(z_1 - q) - K\,(z_2 - z_1) - C\,(\dot{z_2} - \dot{z_1})$$

The main emphasis of this work is on designing a better and more efficient algorithm to solve the optimization problem relevant to the vibrations in vehicle suspension. This improvement is visualized to be possible because the algorithms in the literature provide near optimal solutions. System parameters taken from literature have been widely used as inputs for developing optimization strategies to achieve WBV attenuation [38][45][49][54][55][64][65].

These system parameters are previously obtained experimentally or are validated by independent field measurements.

In the present work, the system parameters reported in literature will be used as inputs. Sample input parameters are furnished in Table 1.

Table 1: Sample vehicle parameters adapted from [33]

Parameter	$m_1(kg)$	$m_2(kg)$	K(N/m)	$k_t(N/m)$	$C(Ns/m)$
Value	55	10	80000	5600	2000

Constraints are set by the practical limitations of components such as suspension displacement etc. Thus, it is a multi-objective optimization problem with conflicting objectives such as minimizing vibration dose value (VDV) and tire displacement. This control problem is hard to optimize even with simple configurations, as the road disturbances are stochastic and transient.

Models with 4-DOF involving half vehicle model and 6 or higher DOF, involving full vehicle model with rotational as well as translational movements have also been constructed and analyzed in literature in recent past. It is estimated that similar vibration level at the operator seat results in different vibration transmission to human body sub-parts. Human body can be divided into head, upper torso, lower torso and pelvis/legs. Each of these sub-parts can be modeled as lumped mass with spring – damper system.

The biodynamic model of human body coupled with the quarter vehicle system gives a more realistic representation of the actual vibration exposure of various human body parts and is the preferred model for vibration analysis. A typical 8-DOF biodynamic model of human body-vehicle system comprising of human body as a lumped mass comprising of four sections and with other four sections being of the vehicle is constructed.

- Head & neck
- Upper torso including arms

- Lower torso
- Pelvis including legs
- Vehicle seat & cushions
- Frame of driver cabin
- Unsprung mass comprising of quarter vehicle other than tire assembly
- Sprung mass comprising of tire assembly

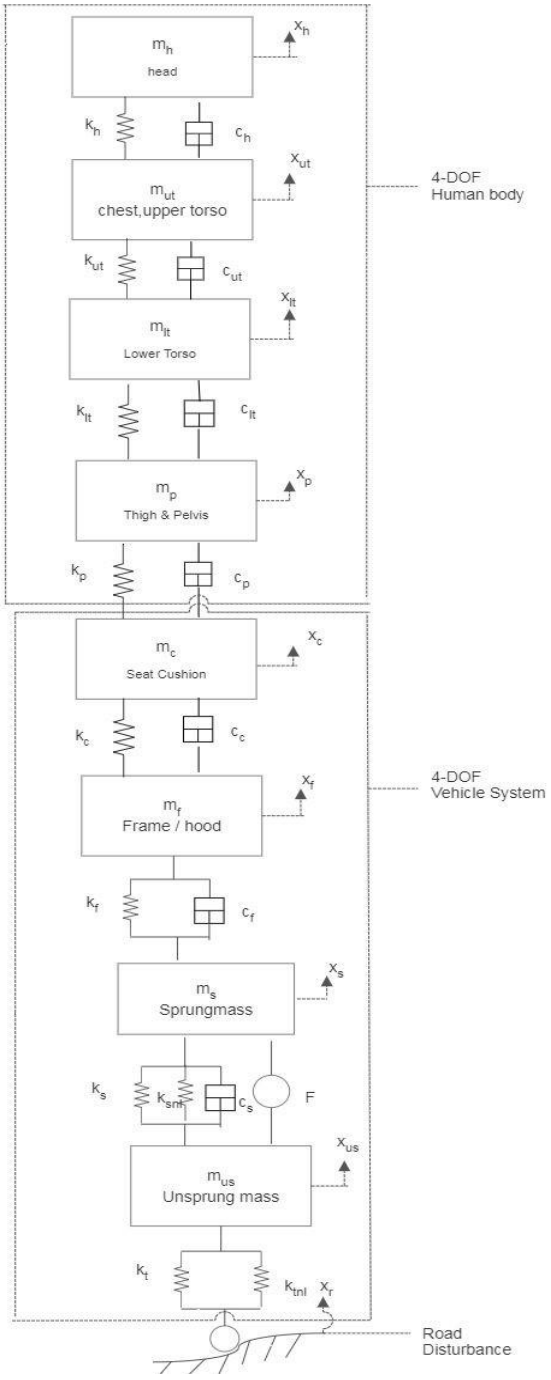

Fig. 3: Schema of 8-DOF Human body-Vehicle system

The system can be modelled using Newton's equations.

For head:

$m_h \,.\, \ddot{x}_h = K_h (x_{ut} - x_h) + c_h (\dot{x}_{ut} - \dot{x}_h)$……(1)

For upper torso:

$m_{ut} \,.\, \ddot{x}_{ut} = k_{ut} (x_{lt} - x_{ut}) + c_{ut} (\dot{x}_{lt} - x_{ut}) - K_h (x_{ut} - x_h) - c_h (\dot{x}_{ut} - \dot{x}_h)$……..(2)

For lower torso:

$m_{lt} \,.\, \ddot{x}_{lt} = k_{lt} (x_t - x_{lt}) + c_{lt} (\dot{x}_t - \dot{x}_{lt}) - K_{ut} (x_{lt} - x_{ut}) - c_{ut} (\dot{x}_{lt} - \dot{x}_{ut})$……(3)

For pelvis/thighs:

$m_p \,.\, \ddot{x}_p = k_p(x_c - x_p) + c_p(\dot{x}_p - \dot{x}_{lt}) - K_{lt} (x_t - x_{lt}) - c_{lt} (\dot{x}_t - \dot{x}_{lt})$…… (4)

For cushion seat:

$mc \,.\, \ddot{x}_c = kc(x_f - x_c) + c_c(\dot{x}_f - \dot{x}_c) - K_p (x_c - x_p) - c_p (\dot{x}_p - \dot{x}_{lt})$……..(5)

For Frame:

$mf. \ddot{x}_f = k_f(x_s - x_f) + c_f(\dot{x}_s - \dot{x}_f) - K_c (x_f - x_c) - c_c (\dot{x}_f - \dot{x}_c)$……..……...(6)

For Sprung mass:

$m_s. \ddot{x}_s = k_s(x_{us} - x_s) + k_{snl}(x_{us} - x_s)^3 + c_s(\dot{x}_{us} - \dot{x}_s) - k_f(x_s - x_f) - c_f (\dot{x}_s - \dot{x}_f) + f$……..(7)

For Unsprung mass:

$m_{us}. \ddot{x}_{us} = k_t(x_r - x_{us}) + k_{tnl}(x_r - x_{us})^2 - k_s(x_{us} - x_s) - k_{snl}(x_{us} - x_s)^3 - c_s(\dot{x}_{us} - \dot{x}_s) - f$ ……(8)

Road roughness is stochastic and it induces transient disturbances. As per ISO standards, roads are classified into 8 categories depending on roughness characteristics. Suitable road profile characteristics can be adopted depending on the intended area. Adapted from literature [34], [35] road profile class B is modelled as:

$\dot{x}_r(t) + 2\pi\eta_0 v.x_r(t) = \sqrt{S_q(\eta_0) \cdot vw(t)}$ ……...(9)

Where

x_r = road profile(m)

$\dot{x}_r$ = rate of change of road profile(m/s)

v= velocity of travel (m/s)

η_0 = Reference Spatial Frequency

S_q(no) = Coefficient of road roughness

w(t) = White noise signal

The objectives for control optimization such as road handling and ride comfort are conflicting.

Constraints of this problem depend on the practical limitations. So, we have a multi-objective optimization problem, with stochastic and transient disturbance, which makes it a hard problem.

4.0 Why does WBV attenuation research need high priority?

Currently installed suspension systems on mobile equipment/vehicles generally have static design values which are frozen at the drawing board stage itself. Such a static and global design methodology has following drawbacks:

i. The suspension system is designed for ideal floor conditions or is based on statistical data of target site conditions on which it may perform satisfactorily. It is common to have real-world site conditions different from design parameters, rendering the designed system ineffective. Even in the given work site, equipment operation is sometimes necessitated in certain pockets where the pathway profile is bad, aggravating the problem.

ii. There are instances, when the suspension system accentuates vibrations rather than attenuating it. This happens when external excitations correspond to the resonance frequency of vibration of the suspension system.

iii. Many equipment such as forklift trucks, cranes, agricultural, mining equipment etc. do not have spring and dampers in their suspension system. This omission is necessitated by limitations of design, stability considerations but exposes the operators to excessive WBV.

iv. Some of the vehicles and equipment have suspension systems designed based on legacy concepts which provide scope for WBV reduction at design stage itself. Due to these inherent shortcomings in prevailing systems, WBVs often exceed the permissible limit. Prolonged exposure to large WBV can cause lower back pain, musculoskeletal disorders and lapse in alertness & cognitive ability. These adverse health effects are well documented as covered in literature review.

v. Hence there is an urgent need to reduce the WBV exposure of drivers/operators on mobile equipment which can make their work conditions safer so as to sustain the quality of their lives.

4.1 Strategies for mitigating the health impact due to WBV exposure

Researchers have used various approaches to mitigate the health effects to which operators of material handling equipment are exposed. Some of these strategies are a combination of postural correctives, visibility improvement measures etc. together with the WBV reduction strategies [36].

There are other confounding factors which might also be partly responsible for the health impact experienced by the operators exposed to WBV. These can be broadly classified into

- Factory/on-site attributes such as quality of floor/pathway at site, rotational shift work assignment, skilling operators on right practices, increasing awareness on WBV, regular upkeep and maintenance of equipment
- Behavioral attributes at workplace such as taking frequent breaks, going slow on bad floors
- Lifestyle attributes of operators such as up keeping fitness levels, smoking and dietary habits, fitness and
- Genetic predisposition of operators, general fitness levels, exercise

Depending on above factors, the threshold limit of WBV exposure impacting the health of operators can vary vastly. Specific localized action on some of the above parameters can help in reducing the health impact on operators to some extent. But the potential of such strategies is limited as they cannot assure satisfactory results in all the applications and for all conditions. Hence, the scope of this research will be restricted to reduction of WBV as the primary mitigation strategy. Succeeding sections are restricted to WBV attenuation strategies.

4.2 The way ahead for WBV attenuation

Most of the material handling equipment operating currently such forklifts or cranes, farm equipment such as agricultural tractors, passenger vehicles such as cars, motorbikes, helicopters, marine boats, transport vehicles such as heavy and off-road vehicles, and earth moving equipment such as loaders dumpers etc. use conventional systems. These are not adequate for attenuating WBV attenuation which impacts the health of operators/passengers. This is established by high odds ratio for health damage of this category of operators. Limited availability of proven, efficient and commercially available technologies and static response of currently installed systems to vibrations is resulting in perpetuation of these risks.

At present, in passive systems, the suspension parameters are optimized at the design stage and the system does not permit any controls. AI has been successful in solving many real-world problems because of its complex problem-solving ability and fast computation. AI approaches have proven to be the excellent tools for design because of their ability to churn out the best parameters even with limited and unclear data. Currently installed suspension systems provide scope for improvement in the light of better understanding of system-human response and superior design methodologies using AI. These provide scope for parametric design optimization for WBV attenuation[37][38][39].

Advancements in instrumentation technologies and controls, such as MR dampers, sensors, motors in semi-active and active suspensions have made these suspensions highly responsive and reliable[40]. These have created new possibilities for controlling the response of the suspension system in real time depending on external excitation and enabling faster dissipation of vibrations. Hence, the design of suspension system using intelligent approaches, has the potential for improvement[41]. Emerging technologies and instruments have opened new opportunities for designing a dynamic and responsive suspension system. Together, these provide a ray of hope for designing a dynamic system which can respond to onsite conditions in real time and ensure safe working conditions.

Some researchers have used soft computing tools for parametric optimization in passive systems[42]. In active and semi active suspensions, controls are possible and they can also be optimized in real time. Various approaches for control have been used such as proportional-derivative (PD) control, proportional-integral (PI) control, proportional integral derivative (PID) control, sliding mode control (SMC), linear quadratic regulator (LQR) control[30]. Intelligent approaches such as GA, ANN, PSO, EA, Deep learning, FLC and hybrid systems are increasingly being used for controls[43][44][45][46][47]. Thus, three broad directions in which the research efforts have been directed for WBV attenuation are:

- Conventional product improvement and Traditional control approach
- Design approach for parametric optimization of equipment for WBV attenuation
- Control approach for WBV attenuation in real time

4.2.1 Conventional product improvement approach

There are some incremental improvements in WBV attenuation reported based on newer materials used in components or changes in design. In one study, a new type of composite rubber springs was used for better control over vibration transmission. It was reported to have acceptable transmissibility of acceleration [48]. Vibration isolators with negative stiffness have been employed in another study recently and found to have considerable positive impact on the comfort level (Papaioannou et al., 2020). The conventional suspension systems have evolved over many decades for its concept and design. This limits the scope for large improvements and out of the box approach. However, the pace of new component development and advancements in material of construction or such other factors can provide avenues for reduction of WBV attenuation to some extent.

A lot of revolutionary developments such as autonomous vehicles, flying cars, robotics for material handling, etc., are also progressing at rapid pace. Such major technological advancements can significantly impact the WBV landscape by ushering in a paradigm shift in the mitigation approach. Prototypes of such vehicles and systems are already under development. Autonomous vehicles may lead to redeployment of professional operators to other jobs eliminating the risk of prolonged WBV exposure, limiting its impact on operator health.

The universal deployment of such systems may still take many more years. Moreover, cost benefit analysis may necessitate the continuation of conventional systems also for a considerable time. This interim period of transition is long enough to impact the quality of life of exposed operators/professionals, making it essential to explore other approaches on priority.

4.2.2 Design approach for parametric optimization for WBV reduction

External road induced vibrations are complex and random. Biodynamic models and human response are complex. Vehicle systems for WBV attenuation also comprise of components which demonstrate dynamic non-linearity. All these factors make the modelling and design optimization for WBV, a challenging task. Hence analyzing the existing equipment models provide scope for improvement.

Using soft computing strategies, and with multi-disciplinary collaboration, it has been feasible to demonstrate marked improvement in WBV reduction. Table 1 provides the literature review on design

approach employed for WBV attenuation using soft computing tools. Table 2 provides literature review of design approach for WBV attenuation.

Notations used:

EA: Evolutionary Algorithm

FL: Fuzzy Logic Controller

ANN: Artificial Neural Network

GA: Genetic Algorithm

PSO: Particle Swarm Optimization

HS: Harmony Search

PVSS: Passive Vehicle Suspension System

AVSS: Active Vehicle Suspension System

SVSS: Semi-active Vehicle Suspension System

CAPSO: Chaos Accelerated Particle Swarm Optimization

PI: Proportional Integral

PID: Proportional Integral Derivative

LMI: Linear Matrix Inequality

ANFIS: Adaptive Neuro Fuzzy Inference System

HANFISPID: Hybrid Adaptive Neuro Fuzzy Inference System Proportional Integral Derivative

Table 2. Synthesis of Literature on design approach for WBV attenuation employing soft computing tools

S.No.	Approach	Problem statement/Model construction	Model validation	Solution strategy	Results	Year	Journal	Author(s)
1	EA	7-DOF full car model - Using linear approach - uncertain road disturbances approximated by a white noise function as per Class B of road roughness. A single objective function with weight allocation based on real implications is assigned to vertical acceleration, roll and pitch along with suspension displacement. Vehicle is simulated for travel speed of 60kmph on a road profile as per class B of road roughness.	Mathematical model of passive system is synthesized and parameters optimized. No information on experimental validation of the model.	GA is used for design optimization of suspension stiffness. The objective function is evaluated in MATLAB.	For the given car's parameter values and constraints, the best value of spring stiffness obtained was 26,175 N/m and it is recommended for this car design.	2019	International Journal of Vehicle Structures & Systems	Avesh M., Srivastava Rajeev, Sharma Rakesh Chandmal[49]
2	EA	A 7-DOF qtr. car model developed analytically for vertical displacement using state space matrix is compared with the model developed using MATLAB Simulink. Problem formulation is in two steps: first one is for design of PVSS and second one is for optimization of controls. Accordingly, the two stages of problem formulation are i) design of optimal Spring stiffness and dampness coefficient of PVSS and ii) optimized of control strategy for AVSS. The measures to assess the objectives are vertical displacement of sprung mass and body acceleration	The MATLAB Simulink model is first validated for vertical displacement using step input disturbance with delay which is found to be similar to the plotting based on analytical model involving state space matrix. No information on experimental validation of the model is presented.	i) GA is used for optimization of design of spring stiffness and dampness coefficient of passive suspension ii) PI controller is used for optimization of control performance in active suspension system.	Results showed improvement in problem objectives with the parameters obtained by GA when compared to original spring stiffness and dampness. The results are further improved with PI controller using active suspension.	2017	Alexandria Engineering Journal	A.E. Gewedda, M.A. El-Gohary, A.M. El-Nabawy, T. Awad [50]

3	EA	A 2-DOF Kineto-dynamic model of seat suspension was formulated for four different classes of earth moving equipment. Excitation signals were synthesized using vibration spectra of equipment superimposed with filtered shock pulses. Design objectives are reduction in VDV and Seat effective amplitude transmissibility (SEAT).	Kinetodynamic model of seat is validated in two stages. In the first stage, the effective vertical suspension forces are compared with the multi body dynamic model made on ADAMS platform. In the second stage, frequency response characteristics of the kinetodynamic model is compared with laboratory measured data for air seat suspension.	Final objective function is analyzed as a constrained optimization problem and solved using GA in MATLAB. Two stage optimization methodology is followed. In the first stage, the air stiffness is optimized by simulating the system under various conditions. In the second stage the dampness characteristics are optimized.	i) Air stiffness: The optimal coordinates of the air spring attachments are obtained from solutions of the minimization problem in Equation (24), as: $l5 = 0.01$ m, $l6 = 0.05$m and $\eta = 1.46$ rad. The minimization problem is solved subject to limit constraints: 0 < suspension length parameter < 0.1792 and 0 <cross bar angle $<\pi$. Natural frequency of the system (excluding the cushion) was permitted to vary in the 1.25 to 1.35Hz range to achieve vibration isolation. ii) Optimal suspension damping parameters and coordinates of the damper mounts for the selected classes of vehicle vibrations superimposed with filtered shock pulses are also obtained.	2017	Vehicle System Dynamics	Wen-Bin Shangguan, Yijie Shui and Subhash Rakheja [42]

4	EA	A 9-DOF, mathematical model of human-crane-rail system was constructed. Fechner's law of psychophysics was used to establish an evaluation model for human vibration comfort. As per this model, annoyance rate was used as a measure of the impact of vibration on human comfort and it is treated as objective function. Basic variables to be optimized were the structure parameters for crane structural design.	Performance of the system model was compared, before and after design optimization, in MATLAB to validate the efficacy of design optimization. No information on experimental validation of the model was presented.	Newmark method to solve the vibration equation and calculate the root mean square of the weighted acceleration. PSO algorithm is used to optimize the crane structural design.	The proposed model and method are used to optimize the design of a double-girder 100 t-28.5 m casting crane, and the optimal parameters are obtained. Comparison of results achieved after design optimization showed 42% reduction in peak acceleration of human body vibration and 55% reduction in weighted RMS acceleration. Annoyance rate is reduced from 28% to 9%.	2017	Shock and Vibration	Xin, Yunsheng Xu, Gening Su, Nina [51]
5	EA	A 2-DOF biodynamic model is derived based on experiments on 5 subjects for predicting human vibration transmissibility to spine using ANN in part 1. Objective function is derived based on multi variate regression analysis comprising of C and K values. Boundaries for these are set based on the limits of practically available suspensions. It is then minimized using 3 EA strategies and compared for best design. The seat suspension parameters optimized are - stiffness and dampness.	ANN based model of human vibration transmissibility is validated by multivariate regression analysis of model prediction and experimentally measured results of human vibration transmissibility (in Part1.)	EA strategies used for optimization are HS, PSO and GA.	It is found that the best parameters for stiffness and dampness are 7,950 N/m and 125 Ns/m resp. The design optimization achieved with HS are superior compared to PSO and GA.	2014	Journal of Low Frequency Noise Vibration and Active Control	Goharimohammad, Tahmasebi Mona [52], [53]

6	EA	A 4-DOF half car model is formulated. Human body model with 4-DOF is also formulated comprising 4 sections - head, upper torso, lower torso, thighs. Objective function is proposed consisting of head acceleration, seat suspension deflection and seat acceleration with wt. factors of 0.5, 0.3 and 0.2 resp. Disturbance is modelled as sinusoidal function for the vehicle travelling at constant speed of 20kmph on a hump of 0.35m height. Optimal values are assessed for stiffness and dampness of FW, RW and Seat suspension.	MATLAB Simulink is used for comparison of the head accn, seat accn and seat suspension deflection for the GA optimized system vis a vis earlier system.	GA is used for optimization of objective function	Design Optimization done for stiffness and dampness of suspensions of front wheel, rear wheel and seat. MATLAB Simulink results are plotted for comparison with original system which shows over 80% improvement in suspension peak displacement and acceleration.	2013	Intelligent Control and Automation	Abbas Wael, Emam Ashraf ,Badran Saeed, Shebl Mohamed,Abouelatta Ossama [54]
7	EA	A 5-DOF half car model is constructed with 5 conflicting objective functions, viz., seat accn, fwd. and rear sprung mass damper velocities, and fwd. & rear sprung mass displacements. The design variables of optimization are seat suspension dampness and stiffness, fwd. & rear suspension dampness & stiffness, and seat position relative to CG.	Superiority of the optimization process is pointed out based on comparison with reported literature.	A new Multi objective Uniform diversity GA(MUGA) with diversity preserving mechanism is used for Pareto Optimizati-on of 5 objectives	Results of 5 objective optimization include 2 objective optimization parameters as pareto frontiers. Overall results shown improvements in objective function constituents.	2010	Engineering Applications of Artificial Intelligence	Nariman Zadeh N., Salehpour M., Haghgoo E., Jamali A. [55]

4.2.3 Control approach for WBV attenuation in real time

The vibrations induced by external sources such as those encountered during equipment transit on rough pathways are generally random and large. These may be difficult to manage based on design approach alone. Hence a lot of research effort is focused on the control approach for the WBV attenuation[56]. To achieve better WBV attenuation, control strategies in real time are also promising [57][58].

There are two major categories of suspension control systems:

- Semi-active suspensions and

- Active suspensions

In Semi-active suspension, such as Magnetorheological dampers and Electrorheological dampers, the dampness characteristics can be varied based on the control decisions in real time. Many of these systems have response time in milliseconds, which makes it possible to deploy these systems for vibration dissipation in real time. There are no external forces acting on the system to counter the vibrational deflections in these systems.

In active suspensions, there is an external force acting on the suspension system to dissipate the vibrations quickly. With the development of accurate and responsive hydraulics, it is now possible to cull the vibrations before they get transmitted to the operators. One drawback of this system, is the power loss for vibration dissipation in such systems. Another drawback of these systems is the relatively high cost of such suspension control systems.

A common drawback of both of these suspension systems is system reliability and stability of control. In the face of a large number of control sensors used, they are prone to system failure. Also, accurate execution of control strategy is required for the control system to be effective.

Table 3, provides the synthesis of literature for the control approaches employing intelligent strategies.

Table 3. Synthesis of Literature review on control approach for WBV attenuation employing intelligent strategies

S.No.	Approach	Problem statement/Model construction	Model validation	Solution strategy	Results	Year	Journal	Author(s)
1	E A	7-DOF full car model - Using linear approach - uncertain road disturbances approximated by a white noise function as per Class B of road roughness. A single objective function with weight allocation based on real implications is assigned to vertical	Mathematical model of passive system is synthesized and parameters optimized. No information on experimental	GA is used for design optimization of suspension stiffness. The objective function is evaluated in MATLAB.	For the given car's parameter values and constraints, the best value of spring stiffness obtained was 26,175 N/m and it is recommended for this car design.	2019	International Journal of Vehicle Structures & Systems	Avesh M., Srivastava Rajeev, Sharma Rakesh Chandmal[49]

		acceleration, roll and pitch along with suspension displacement. Vehicle is simulated for travel speed of 60kmph on a road profile as per class B of road roughness.	validation of the model.					
2	EA	A 7-DOF qtr. car model developed analytically for vertical displacement using state space matrix is compared with the model developed using MATLAB Simulink. Problem formulation is in two steps: first one is for design of PVSS and second one is for optimization of controls. Accordingly, the two stages of problem formulation are i) design of optimal Spring stiffness and dampness coefficient of PVSS and ii) optimized of control strategy for AVSS. The measures to assess the objectives are vertical displacement of sprung mass and body acceleration	The MATLAB Simulink model is first validated for vertical displacement using step input disturbance with delay which is found to be similar to the plotting based on analytical model involving state space matrix. No information on experimental validation of the model is presented.	i) GA is used for optimization of design of spring stiffness and dampness coefficient of passive suspension ii) PI controller is used for optimization of control performance in active suspension system.	Results showed improvement in problem objectives with the parameters obtained by GA when compared to original spring stiffness and dampness. The results are further improved with PI controller using active suspension.	2017	Alexandria Engineering Journal	A.E. Gewedа, M.A. El-Gohary, A.M. El-Nabawy, T. Awad [50]
3	EA	A 2-DOF Kineto-dynamic model of seat suspension was formulated for four different classes of earth moving equipment. Excitation signals were synthesized using vibration spectra of equipment superimposed with filtered shock pulses. Design objectives are reduction in VDV and Seat effective amplitude	Kinetodynamic model of seat is validated in two stages. In the first stage, the effective vertical suspension forces are compared with the multi body dynamic model made on ADAMS platform. In	Final objective function is analyzed as a constrained optimization problem and solved using GA in MATLAB. Two stage optimization methodology is followed.	i) Air stiffness: The optimal coordinates of the air spring attachments are obtained from solutions of the minimization problem in Equation (24), as: $l5 = 0.01$ m, $l6 = 0.05$m and $\eta = 1.46$ rad. The minimization problem is solved subject to limit constraints: 0 < suspension length	2017	Vehicle System Dynamics	Wen-Bin Shangguan, Yijie Shui and Subhash Rakheja [42]

		transmissibility (SEAT).	the second stage, frequency response characteristics of the kinetodynamic model is compared with laboratory measured data for air seat suspension.	In the first stage, the air stiffness is optimized by simulating the system under various conditions. In the second stage the dampness characteristics are optimized.	parameter < 0.1792 and 0 <cross bar angle <π. Natural frequency of the system (excluding the cushion) was permitted to vary in the 1.25 to 1.35Hz range to achieve vibration isolation. ii) Optimal suspension damping parameters and coordinates of the damper mounts for the selected classes of vehicle vibrations superimposed with filtered shock pulses are also obtained.			
4	EA	A 9-DOF, mathematical model of human-crane-rail system was constructed. Fechner's law of psychophysics was used to establish an evaluation model for human vibration comfort. As per this model, annoyance rate was used as a measure of the impact of vibration on human comfort and it is treated as objective function. Basic variables to be optimized were the structure parameters for crane structural design.	Performance of the system model was compared, before and after design optimization, in MATLAB to validate the efficacy of design optimization. No information on experimental validation of the model was presented.	Newmark method to solve the vibration equation and calculate the root mean square of the weighted acceleration. PSO algorithm is used to optimize the crane structural design.	The proposed model and method are used to optimize the design of a double-girder 100 t-28.5 m casting crane, and the optimal parameters are obtained. Comparison of results achieved after design optimization showed 42% reduction in peak acceleration of human body vibration and 55% reduction in weighted RMS acceleration. Annoyance rate is reduced from 28% to 9%.	2017	Shock and Vibration	Xin, Yunsheng Xu, Genin g Su, Nina [51]

5	EA	A 2-DOF biodynamic model is derived based on experiments on 5 subjects for predicting human vibration transmissibility to spine using ANN in part 1. Objective function is derived based on multi variate regression analysis comprising of C and K values. Boundaries for these are set based on the limits of practically available suspensions. It is then minimized using 3 EA strategies and compared for best design. The seat suspension parameters optimized are - stiffness and dampness.	ANN based model of human vibration transmissibility is validated by multivariate regression analysis of model prediction and experimentally measured results of human vibration transmissibility (in Part1.)	EA strategies used for optimization are HS, PSO and GA.	It is found that the best parameters for stiffness and dampness are 7,950 N/m and 125 Ns/m resp. The design optimization achieved with HS are superior compared to PSO and GA.	2014	Journal of Low Frequency Noise Vibration and Active Contrl	Goharri Mohammad, Tahmasebi Mona [52], [53]
6	EA	A 4-DOF half car model is formulated. Human body model with 4-DOF is also formulated comprising 4 sections - head, upper torso, lower torso, thighs. Objective function is proposed consisting of head acceleration, seat suspension deflection and seat acceleration with wt. factors of 0.5, 0.3 and 0.2 resp. Disturbance is modelled as sinusoidal function for the vehicle travelling at constant speed of 20kmph on a hump of 0.35m height. Optimal values are assessed for stiffness and dampness of FW, RW and Seat suspension.	MATLAB Simulink is used for comparison of the head accn, seat accn and seat suspension deflection for the GA optimized system vis a vis earlier system.	GA is used for optimization of objective function	Design Optimization done for stiffness and dampness of suspensions of front wheel, rear wheel and seat. MATLAB Simulink results are plotted for comparison with original system which shows over 80% improvement in suspension peak displacement and acceleration.	2013	Intelligent Contrl and Automation	Abbas Wael, Emam Ashraf ,Badran Saeed, Shebl Mohamed,Abouelatta Ossama [54]
7	EA	A 5-DOF half car model is constructed with 5 conflicting objective functions,	Superiority of the optimization process is	A new Multi objective Uniform	Results of 5 objective optimization include 2	2010	Engineering Applications	Narimman Zadeh N.,

		viz., seat accn, fwd. and rear sprung mass damper velocities, and fwd. & rear sprung mass displacements. The design variables of optimization are seat suspension dampness and stiffness, fwd. & rear suspension dampness & stiffness, and seat position relative to CG.	pointed out based on comparison with reported literature.	diversity GA(MUGA) with diversity preserving mechanism is used for Pareto Optimization done of 5 objectives	objective optimization parameters as pareto frontiers. Overall results shown improvements in objective function constituents.		of Artificial Intelligence	Salehpour M., Haghgoo E., Jamali A. [55]

5.0 Gap Analysis

Suspension system design/control involves trade-off between conflicting objectives such as road handling and ride comfort while meeting the load carrying criterion. Depending on the type of suspension system, we may have other objectives such as minimization of control force or damper displacement. The external disturbance signal is random and transient, which is another challenge in designing a practical system. System complexity is further enhanced due to non-linearity in stiffness exhibited by the components of system such as tires and suspension spring. Practical constraints of available components also set the boundary value limitations. Another challenge is the deviation in system performance under practical conditions which are different from the theoretical performance. Relative difficulty in achieving improvement in WBV attenuation in practical systems arise due to all these challenges, thus risking the lives and health of countless operators.

Many studies have analyzed the performance of suspension system considering the road disturbance as a step function or sinusoidal function. Recent studies have analyzed road disturbance modelled as a PSD function whose parameters are defined as per ISO 8608(2016), depending on the class of road. So, suspension system design / control has been considered as a multi-objective or many-objective optimization problem involving random and transient inputs. Estimating the impact on the human operator utilizing a biodynamic model is still evolving. When it comes to control strategies, the system should also be responsive and complete the computation in short duration (~ 40ms) so as to bring about any meaningful reduction in Whole-body vibration. Commercial deployment of any strategy, requires the solution to be economical.

The study of literature on WBV attenuation in suspension systems shows gaps in

- Parametric design approaches of the passive suspension system and
- Control strategies for WBV attenuation in real time in active/semi-active suspension systems.

5.1 Gaps found in Parametric Design Approaches

The study of literature shows the gap in the strategies used for design optimization which need further investigation. Various EA approaches have been used for multi-objective optimization problems in this application. EAs are stochastic search and optimization methods based on the principles of biological evolution. EAs are robust and are good at global search capabilities. But the parameters of EA have to be designed properly to achieve good balance between exploration and exploitation. The combinatorial optimization problem becomes more complex in suspension design domain, when the stochastic disturbance signal is introduced in the suspension models involving higher degrees of freedom coupled with non-linearity in the suspension parameters. To overcome these, Quantum Inspired Evolutionary Algorithms (QIEAs) are promising, and are described in brief in succeeding section. The performance of QIEAs have been validated by the benchmark combinatorial optimization problems, such as 0/1 knapsack problem. Certain improved versions of QIEA, such as QIEA-PSA have also been applied with advantage on some variants of difficult knapsack problems [66]. Quantum Inspired Evolutionary Algorithm (QIEA) achieves superior results when compared to GA, in various other studies involving a variety of benchmark optimization problems[67]. This approach has not been investigated fully in the domain of suspension system parametric optimization for WBV attenuation.

Another gap area identified is the application of Hybrid strategies based on Fuzzy logic, Neural Networks, GA. These have also been successful for certain multi-objective optimisation problems and can generate better solutions.

So, implementation of one or more of these for design optimization, is a novel approach for suspension system parametric design optimization, which needs to be investigated.

5.1.1 Quantum Inspired Evolutionary Algorithm (QIEA)

Quantum inspired Evolutionary Algorithms are EAs which use the concept and principles of quantum computing. In QIEA also we have a certain method for representing individuals, evaluation function

and population dynamics. The smallest bit of information is Q-bit which is defined by a pair of numbers (α β), such that

$|\alpha|^2 + |\beta|^2 = 1$

Where, the probability of assigning "0" state depends on $|\alpha|^2$, and that of assigning "1" depends on $|\beta|^2$.

A string of Q-bits represent the individual. A variation operator is introduced in QIEA which is defined as Q-gate, to drive individuals towards better solution. The basic procedure for implementing QIEA given by Han & Kim is presented here [68].

5.2 Gaps found in Intelligent Control Approaches

Study of literature shows that GA and other EAs have been used for optimization of controller parameters such as FLC membership functions. With better tuning of controller parameters, we might achieve superior performance in the control objectives. The effectiveness and applicability of QIEA is demonstrated in the experiments on knapsack problem, which are well-known combinatorial optimization problems. The results of the experiments show that QIEA performs better than conventional GA even with small population and without premature convergence [68]. The ability to explore the search space with few observations and converge in short time will be a major advantage in suspension control domain where swift action by the control system will lead to faster attenuation of vibrations. In view of these requirements, latest approaches such as Quantum Inspired Evolutionary Algorithms (QIEAs) are a natural choice. But the literature survey has not shown the implementation of this approach in suspension control domain.

Hybrid strategies based on Fuzzy logic, Artificial Neural networks and Genetic Algorithm have also been successful in multi-objective optimisation problems and provide scope for further investigations.

Another gap identified is that NSGA-II & other approaches for multi-objective optimization problems have been used in literature, whereas problem formulation is that of a many-objective optimization problem (MaOOP). NSGA-II is known to work well for multi-objective optimization problems but its performance deteriorates when applied to MaOOP. So if we attempt to solve this problem with latest strategies for MaOOP, we may get better results[69]. This gap also needs further investigation.

So, implementation of one or more of these will be a novel approach for the multi-objective suspension controller design application.

6.0 Proposed Work

The detailed literature review presented in the previous sections clearly demonstrate the importance of the problem of reducing WBVs, to ensure that long term exposure to WBVs do not cause health hazards to the drivers. This is the primary motivation for undertaking this work. Existing body of work for WBV attenuation has primarily focused on passenger cars and has not dealt with the problem in the other vehicles, viz., forklifts, overhead cranes, tractors, etc. Even in case of passenger cars the models developed have considered limited degrees of freedom in many works. Further, the recent techniques for intelligent controller design and parametric design optimization as elucidated in previous section have not been explored at all in this domain.

An attempt is proposed to be made in this research effort to explore these new techniques for the WBV reduction problem. Specifically, efforts will be made in the following directions.

1. Designing an improved suspension of a passive system for WBV attenuation, using soft computing strategies. This involves,
    a. Modeling the test case equipment and obtaining its parameters
    b. Mathematical Formulation of design problem, defining the performance indicators, constraints and
    c. Optimization of suspension system using soft computing strategies exploiting the identified gaps and comparison of its performance with that of the original system using simulation.
2. Designing an intelligent system for controlling suspension parameters of an active/ semi-active suspension for WBV attenuation in real time. This would involve,
    a. Developing a model of the suspension system of the test case vehicle with the estimation of various parameters
    b. Deriving a mathematical formulation of control problem, defining the objectives, constraints, and control strategies for an active / semi-active suspension system

c. Developing intelligent strategies for suspension control exploiting the identified gaps, comparing the performance with other control strategies and corresponding passive system using simulation

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